Nutrition and Foods as Related to Space Flight

For book titled Physiological Adaptations to Space Flight

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Introduction

U. S. space food development began with highly engineered foods that met rigid requirements imposed by the spacecraft design and short mission durations of the Mercury and Gemini programs (Nanz et al., 1967). The lack of adequate bathroom facilities and limited food storage capacity promoted the development of low fiber diets to reduce fecal output. As missions lengthened, space food systems evolved, with the most basic design consideration always being the method of water supply. On the Apollo spacecraft, where water was abundant as a by-product of fuel cell electricity generation, dehydrated food was used extensively (Bourland et al., 1977; Smith et al., 1975). Such food has little advantage when water has to be transported to space to rehydrate it; therefore, more complex food systems were planned for Skylab, which used solar panels rather than fuel cells for electricity generation. The Skylab food system, the most advanced used in space to date, included freezers and refrigerators (Johnston, 1977), increasing the palatability, variety, and nutritional value of the diet. On the Space Shuttle, power and weight constraints precluded the use of freezers, refrigerators, and microwave ovens. The availability of fuel cell by-product water was conducive to a shelf-stable food system with approximately half of the food dehydrated and the remainder made up of thermostabilized, irradiated, and intermediate-moisture foods (Bourland, 1993).

For the Shuttle-Mir program, a system that combined U. S. and Russian menus and foods was used on Mir during shared operations. The international space nutrition requirements (Table 1) that were established for Shuttle-Mir will also be used on the International Space Station, a cooperative project of the U.S., 10 European countries, Canada, Brazil, Japan, and Russia. The station will use solar panels for power generation. Some water will be recycled on the station, but not enough for food use. A Shuttle-Mir-type food system is planned for the Assembly Phase, with most of the food being delivered by Russian cargo vehicles. A frozen food system with a microwave convection oven is planned for the Assembly Complete Phase, now scheduled for 2004.

History of Space Food

Food on Early Missions

Project Mercury (1961-1963), the first U.S. endeavor to place humans in Earth orbit, comprised two suborbital flights followed by three orbital flights lasting up to 34 hours. The suborbital flights carried no food. John Glenn became the first U.S. astronaut to eat in space when he consumed applesauce from a tube on the third Mercury mission in 1962 (Nanz et al., 1967). Other foods introduced on later Mercury missions included bite-sized cubes of a high-calorie mixture of protein, high-melting-point fat, sugar, and fruit or nuts. Food research and development emphasis during the Mercury period was on calorie-dense, nutritious, and palatable food. Since these missions were short, no provisions were made for specific food storage aboard the spacecraft.

The 10 Gemini missions consisted of crews of two in flights up to 14 days. A food system including formulations and packaging was designed for the Gemini program (Nanz et al., 1967). The menu consisted of 2500 kcal per person, but was restricted in weight and volume; therefore,

concentrated foods were emphasized. Food, packaging specifications, and testing procedures was developed to ensure maximum safety. Analysis methods were established to ensure that food met the Gemini spacecraft requirements, as well as the nutritional, sensory, and microbiological prerequisites. These methods formed the beginning of the Hazard Analysis Critical Control Point system which is in worldwide use in the food industry (Heidelbaugh, 1966). Packaging material was developed with high water vapor and oxygen barrier properties to withstand the rigors of space flight. Crews ate bite-sized cubes or foods squeezed from tubes. Even though the foods met the description of acceptability in ground-based tests, crews did not eat enough in flight and so lost weight (Smith et al., 1971)

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On the Apollo program (1968-1972), with water available as a by-product of the fuel cell electric power generation, dehydrated food was the solution to restricted weight and volume allowances. The initial Apollo food system was basically the same as that provided on the Gemini program; however, food research for the Apollo Applications Program, a precursor of Skylab, was also applied to Apollo. It included the use of retort pouches and canned products, and the concept of eating from open containers with utensils. Increased variety and improved quality became important design factors (Smith et al., 1975).

The Apollo missions were the first to use utensils for eating, the first to use retort pouches (they were called "wet packs" then), and the first to use irradiated food. Early in the Apollo program, the spoonbowl package was developed as a solution to the problem of direct package-to-mouth consumption. Water was added through a one-way water port. Then the top of the package was cut open and the contents were consumed with a spoon. Although this approached normal eating procedures, it required both hands: one to hold the package and one to hold the utensil. The spoonbowl was used on Apollo, Skylab, Apollo-Soyuz, and the first four Shuttle missions.

Skylab Food System
The Skylab program (1973-1974) included the most extensive metabolic study thus far undertaken by the U.S. in space; therefore, data from Skylab still provide the baseline nutritional information for space. A preflight trial production of all the food provided samples for analysis and established baselines. The trial food was also used in a 56-day closed-chamber test with three astronauts. Both trial and flight foods were analyzed for 37 different nutrients. Specific levels of six nutrients were maintained for 21 days preflight, throughout the flight, and 18 days postflight.

All of the planned food for the Skylab program was launched with the first mission; thus it was over 2 years old when the last crew consumed it. Most of the food was packaged in aluminum cans to maintain the 2-year shelf life (Klicka and Smith, 1982). Frozen food which required heating and some thermostablized items were packed in cans with a membrane under the lid to prevent spilling while heating and to facilitate opening in microgravity. Before launch, the cans were sealed in canisters designed to withstand the pressure change from 14.7 on the ground to 5 psia in the spacecraft (Johnston, 1977). The Skylab food maintained quality

throughout the 2-year period, even though cabin temperatures reached 54°C early in the mission when a solar panel failed to deploy. The high temperature caused some browning, but the food was still edible, thanks in part to the high-barrier packaging. Vitamins were supplied for the last two missions to make up for any that may have been destroyed by heat. When the Skylab 4 mission was extended from 56 days to 84, high-caloric-density bars were developed to provide approximately half of the calories for the extended time.

The first U.S. spacecraft to have freezers, refrigerators, and food warmers, Skylab had a palatable and varied diet chosen from 72 foods with a 6-day-cycle menu. From the freezers, the crews were able to have such foods as ice cream, filet mignon, and lobster; from the refrigerator they had chilled beverages and desserts. The dining table had built-in food heaters with timers for advanced preparation of food. The astronauts' nutritional intake was the best recorded to date on U.S. space flights.

Shuttle Food System
The U.S. Space Shuttle (1981-present) food system has no freezers and refrigerators because of the short duration of planned missions and the lack of storage room and electrical power on the orbiter (Bourland et al., 1977). The fuel cells that produced electricity generated by-product water that could be used with dehydrated food (Figure 1).

A new space food system concept based on eating from open containers on a meal tray was used for the Shuttle food system. A rehydratable package was developed that permitted eating from the tray and eliminated over 30 package fabrication steps associated with the spoonbowl package. A single package design was used for food and beverages. A galley with a rehydration station and convection oven permitted addition of hot or cold water and provided the ability to heat food to serving temperatures. The number of food choices for Shuttle flights is greater than that for previous missions.

The menu plan is based on crew input, to allow for a personal-preference menu for each person. They select their menu from 150 food items far enough in advance of a mission to use them in training exercises. The dietitian analyzes each menu for its nutrient content and substitutions are recommended to ensure a balanced supply of the nutritional requirements. Most of the menus that are planned from the foods on the current Shuttle list meet all of the nutritional requirements, except that they are high in iron and sodium and may be low in fiber. However, during a flight, crewmembers have the opportunity to exchange meal items and to choose snack or bonus foods from a food pantry. Therefore, actual in-flight dietary intake may not match the nutritionally balanced menu planned before flight. Very few crew complaints are made regarding food quality or food choices. However, despite increased variety of foods, personal-preference menus, hot and cold water, and a reliable oven for heating foods, nutrient intake for Shuttle astronauts has not been adequate (Lane et al., 1994).

Space Station Food System
As part of Phase I of the International Space Station program, an agreement between Russia and the U.S. included several joint missions in which U.S. astronauts lived and worked aboard the

Mir space station. These missions provided the U.S. with long-duration research and experience similar to that planned for the early stages of the ISS. The first Mir mission with U.S. involvement was Long Duration Mission-1 (LDM-1), when an astronaut and two cosmonauts launched in a Soyuz vehicle (the first Russian launch for a U.S. astronaut) and docked with Mir in March 1995. The astronaut remained aboard Mir for 116 days, performing medical experiments. At the end of his stay, the Shuttle on mission STS-71, which also picked up two cosmonauts and delivered two cosmonaut replacements, picked him up. The Shuttle transported the LDM-2 astronaut to Mir in March 1996. U.S. astronauts maintained a continuous presence aboard Mir through May 1998, with stays from 111 to 184 days. The Shuttle made astronaut exchanges (See Figure 2).

Exploration Missions
NASA's long-term future includes extended missions to the Moon, to Mars, or beyond. These longer missions (greater than 6 months) will require that food systems comply with various requirements, some of which have been discussed earlier. Optimizing volume, mass, and energy expenditure will be the primary goal of the mission engineers. Increases in weight and energy supplies would result in prohibitive costs, and additional volume would minimize the number of items that could be brought on board.

The nutritional requirements for such extended missions will need to be met by the food supply alone or by the food supply with supplements. To plan precisely for the food systems, research into the required amount of each nutrient and the bioavailability of nutrients during long-term exposure to a space environment is still needed. Food safety considerations are essential because an outbreak of food-borne illness could be catastrophic. Appetizing food which satisfies a crew's craving for variety in tastes, smells, and textures is an underlying requirement for the food system—after all, the food must be ingested for the nutrients to be delivered. Perhaps most critical for long missions is the importance of the food to crew morale and psychological well-being. Food on Earth is often used for social occasions, to commemorate special events, and as a comfort agent. Such roles will surely be amplified during long-term confinement required for extended space missions. A variety of food system scenarios have been proposed to satisfy these requirements, each of which has advantages and disadvantages.

A bioregenerative system would have the crew growing almost all of their food in hydroponic (or zeoponic) plant-growth chambers (Barta and Henninger, 1996). While some limited plant growth for food production may be possible on the International Space Station or in a transit vehicle on the way to Mars, a complete bioregenerative food system would require large plant growth chambers and significant food processing equipment and thus would be limited to a surface habitat on the Moon or Mars or some other planetary body. NASA has no flight experience with a food system of this type, making it very difficult to predict a weight and volume component. Only food items that could not be grown by the crew (for example, chocolate or cocoa) would be launched from Earth; therefore the weight and volume would be associated with supplies and equipment needed to plant, grow, harvest, process, and store the crops and the ingredients derived from those crops. The system obviously will require a significant initial investment. The color, flavor, and texture of freshly grown food items, lacking in a food system based entirely on rehydratable, thermostablized, or frozen food, would be more

acceptable to the crew and would have a positive psychological effect on them. Raw fruits and vegetables would provide the crew with better nutrition and much more fiber than their processed equivalents. Crops harvested regularly would have less potential for shelf life problems than foods brought from Earth for a lengthy stay such as a 3-year mission to Mars. Another advantage of this system would be crew involvement in the food growth, processing, and preparation. There is evidence from long-duration missions on Mir that the presence of growing plants and the interaction of the crew with those plants has a very positive psychological effect on crewmembers.

Potential disadvantages of a bioregenerative system would include the amount of crew time required to grow, harvest, and process crops and prepares food items. Time needed for these tasks is difficult to quantify at this point; it would depend partly on the degree of automation that can be incorporated into various tasks. A totally plant-based food system would also have the potential for food safety issues. Careful and extensive training of crewmembers in food production and processing techniques would be required to eliminate risks to food safety from the improper handling and storage of crops, ingredients, or finished foods. Because water and waste would be recycled in such a system, the nutrients used for growth of food plants might contain processed waste. Sanitizing agents such as chlorine rinses, routinely used in the food industry, would be devastating to the microorganisms housed in the bioreactor, which might be used to process waste. The possibility of crop failures in a bioregenerative food system must also be considered.

Nutritional content of an exclusively plant-based food system would have to be monitored closely. Previous experience with vegetarian diets has shown that certain nutrients are more difficult to obtain in such a diet (Kloeris et al., 1998). Full crew acceptance of a vegetarian diet would be difficult to obtain. Depending on which crops are available and in what quantities, some supplements and preprocessed items (such as irradiated meat) might need to be supplied

The planetary food system will rely on stored food during construction of the surface habitat, which will include large chambers for growing crops to provide not only food, but also oxygen for the habitat. Integration of these crops into the food system will begin with the substitution of harvested items for similar items in the stored food system. A projected order in which crops will likely be integrated into the advanced life support food production system is depicted in Figure 3. The specialized technologies for crop growth and food processing must meet the constraints associated with crew time, food shelf life, safety, storage area, and power sources.

Space flight poses not only engineering and human physiological challenges but also more subtle ones that may be categorized as performance and behavior. With international crews exhibiting different values and food preferences, maintaining productive teams will continue to be complicated. Yet crewmembers from different countries have many similar professional values and ideas derived from being a part of the space-faring culture. Behavior and performance issues become increasingly important as space missions become longer and crewmember teams become larger and more heterogeneous. The isolated and unique environment of space presents additional stresses. Interpersonal and group relations can affect

mission success (Holland and Marsh, 1994). In any intense, stressful situation with ample responsibilities and schedule pressures, nutritional status may be affected. Space travel is no different. In space flight the most common response to schedule and time limitations is skipping meals and only snacking.

Current Russian and U.S. programs include organized psychological support and training programs to address the full spectrum of requirements, from crew selection through postflight readaptation. Training as a team is stressed, and family support during the mission is strongly encouraged. Food is an integral part of the celebration of family and holiday events, and special foods are provided to enhance the quality of the space flight. These procedures appear to be successful in maintaining high performance standards.

Nutrient Intakes

Table 2 provides the nutrient intakes for the Apollo, Skylab, and Shuttle astronauts. For the Skylab program, nutrient intakes were nearly identical to the nutritional standards of the day. These data demonstrate that adequate intakes can occur. The reason for these good intakes as compared to the other flight programs is probably due to a combination of the intense effort to make sure the crew consumed all their food because they were on metabolic diets and the improved quality of the food. An explanation for the lower intakes during the shuttle flight may be due to lack of time to eat, sleep shifting, and stress, of which all may reduce appetite.

Body Weight and Composition
Body weight usually decreases during space flight (0.5 to 5 kg). Some portion of the weight lost is believed to be water (~900 ml) (Leach et al., 1996; Leach and Rambaut, 1977), lean body mass, and bone (Oganov et al., 1991; Leonard et al., 1983). From long-duration missions that included exercise, there was a resting $RQ > 1.0$, suggesting that some lean body mass was replaced with fat (Lane, 1992; Michel et al., 1977).

Although methods to measure body composition during space flight (such as bioelectric impedance) are being developed, body composition cannot be accurately measured during space flight at this time. Bed rest (-6° head down tilt) and water submersion has been used to model the effect of space flight on body composition (Gretebeck et al., 1995). The supposition that lean body mass is replaced with fat in a microgravity environment was explored by using dual energy x-ray absorptiometry (DEXA) to measure body composition before and after ten days of bed rest (-6° head down tilt) in nine adult men. In this study, body weight did not change (83.7 ± 10.0 kg before vs. 83.6 ± 9.5 kg after bed rest), but body fat increased 0.44 ± 0.67 kg (p<0.05) and lean body mass decreased 0.55 ± 1.14 kg (Lane and Gretebeck, 1994; Leonard et al., 1983; Lane et al., 1983). These findings from bed rest and the preliminary pre- and postflight data from astronauts flying on the Russian space station Mir for three to six months suggest that body weight alone does not accurately reflect changes in energy balance during simulated microgravity and space flight.

ENERGY

Research with astronauts from the 1960s through today has made it clear that providing adequate energy (calories) for optimal health during space flight is multifactorial (Leonard et al., 1983; Michel et al., 1977). Human energy metabolism during space flight has been determined indirectly using several methods: diet history, metabolic-balance studies, recording the disappearance of food, indirect calorimetry measuring respiratory gas production, and using the doubly labeled water method (Lane and Gretebeck, 1994). Skylab crewmembers kept detailed dietary records while participating in metabolic balance studies (Michel et al., 1977). The crewmembers consumed the same amounts of energy before and during flight. Flight duration did not affect the apparent energy intake from foods consumed: [mean (±SD)] at 28 days, it was 11.24 ± 0.59 MJ (2686 ± 141 kcal); at 59 days, 12.30 ± 2.25 MJ (2939 ± 538 kcal); and at 84 days, 12.43 ± 0.33 MJ (2972 ± 78 kcal). However, the type of energy consumed before flight differed from in-flight intake: more carbohydrate and less fat were consumed during flight than before (Lane and Gretebeck, 1994; Lane, 1992; Michel et al., 1977, Lane and Smith, 1999).

Energy utilization has been assessed indirectly during Space Shuttle flights. Mean energy consumption was calculated from disappearance of food from the storage lockers during the first eight Shuttle missions. These data were compared with atmospheric CO_2 produced during each of these flights (Lane, 1992). Mean energy utilization per person ranged from 8.19 to 11.55 MJ/d (1957 to 2760 kcal/d). Although these methods are less reliable than those used on Skylab, the energy utilization values are nonetheless similar. Table 3 shows a comparison of energy studies from space flight.

Actual energy expenditure was measured (Lane et al., 1997) using doubly labeled water. This study demonstrated that human energy requirements during brief space flights of 9-10 days were similar to those on Earth. For the 13 men (moderately active, normal weight), their space flight energy utilization was 8.37 to 12.55 MJ/d (2000 to 3000 kcal/d). Because crew activities were not quantified, this range is very wide and not very helpful. Other variables, such as resting energy expenditure (REE), the level and type of physical activity, and energy substrate (carbohydrate, protein, and fat), can have profound effects on energy requirements. The dietary intake of these subjects was significantly lower than before flight and lower than energy expenditure during flight (Lane and Smith, 1999). The resulting negative balances in energy and fluids early on in a flight produce weight and fluid losses that, if allowed to continue, would pose a significant risk to crew health and performance.

Resting energy expenditure (REE) is a large component of total energy expenditure; thus any changes in REE have a significant impact on energy requirements. Flight data on REE, however, are scarce and must be interpreted cautiously. Kasyan and Makarov (1984) reported respiratory gas exchange data showing that during missions lasting up to five days, energy expenditure in a state of relative rest was increased by an average of 2.64 kJ/min (0.63 kcal/min or 900 kcal/day). Experiments on Skylab also indicated that during five minutes of rest on orbit, oxygen consumption increased (Michel et al., 1977). Leach et al. observed increased levels of thyroxine-stimulating hormone (TSH) and thyroxine during space flight which may contribute to increased REE (Leach et al., 1982). For Skylab, flight iodine was used as a bactericide agent in

the water and may have contributed to the increases observed in TSH levels. Thyroid hormone stimulates oxygen consumption, heat production, and metabolism of protein, carbohydrates, and fats. These observations suggest that REE may be elevated during space flight. However REE has never been measured under controlled conditions in space; until it is, any conclusions regarding REE remain speculative.

Physical activity, by far the most variable component of total energy expenditure, can lead to differences in energy requirements in two individuals with the same REE. Therefore, even though REE is important in estimating energy requirements, it alone is insufficient. Estimates of energy expended during Earth-based physical activity are based on tabulated energy costs for different activities. The valid use of these tables in weightlessness, however, is questionable. The most common, and perhaps best-studied, physical activity on Earth is walking, which cannot be done in space without being restrained to a moving surface such as a treadmill. The metabolic cost of exercise on a cycle ergometer was measured aboard Skylab. In these studies, oxygen uptake at a work load equal to 25, 50, and 75% of each subject's preflight VO_{2max} was slightly, but consistently, less than before flight for all nine Skylab astronauts (Michel et al., 1977). Oxygen recovery was also greater during flight (678 ± 44 ml/min before compared to 742 ± 63 ml/min during). This reduced oxygen uptake and increased oxygen recovery time at the same absolute workload suggests greater anaerobic metabolism and fatigue during work in flight (Michel et al., 1977). These results may also suggest that work in weightlessness require more energy than on Earth. Biomechanical analysis of treadmill exercise has suggested that mechanical efficiency may be reduced during space flight (NASA unpublished), although this may reflect the need for restraining devices in microgravity. On the other hand, tasks that normally would be difficult on Earth, such as moving heavy objects, may be accomplished easily in space.

The availability of nutrient substrates depends on intake and their regulation by the body. Endocrine changes caused by space flight may affect energy utilization. Although one study reports that blood glucose concentration increased slightly and then decreased below preflight levels during Skylab flights, another found no change in blood glucose concentration during Russian missions of 15, 24, 29, and 63 days (Balakhovsky and Orlova, 1978). In a study of insulin regulation during bed rest, six healthy men showed no changes in blood glucose concentrations; however, plasma glucagon and insulin concentrations were higher during bed rest than during the ambulatory control period (Shangraw et al., 1988; Stuart et al., 1990). Insulin resistance has been postulated to increase circulating triglycerides and hence increase the accumulation of body fat. However, serum triglycerides were found to be slightly reduced after Shuttle flights (Leach, 1992; Cintrón et al., 1990). In another study, Grigoriev et al. (1987) compared blood insulin and free fatty acid concentrations in cosmonauts before, one day after, and seven days after space flights of 4 to 14 days. Compared with preflight levels, fatty acid concentrations were lower and serum insulin concentrations higher one day after landing; insulin concentrations remained elevated until seven days after landing. In contrast, no differences were found in blood glucose before and after flight.

Fluid Status

Fluid status has been one of the most extensively researched nutritional issues of space flight. This attention had its inception in the profound changes noted even in the initial flights of Gemini. During the early phase of space flight (1 hour to 1 day), plasma volume decreases. The lack of gravity pulling the blood toward the feet is reflected by the fluid congestion in the head (Leach et al., 1996). The decreased plasma and lack of gravitational pull have immediate effects on the cardiovascular system. Catecholamine receptors and endocrine responses to shifts in fluid status are probably affected. The plasma volume decrease causes an increased concentration of red blood cells (increased hematocrit), which decreases erythropoiesis. Eventually a new set point is reached with about 15% lower plasma volume and red blood cell mass. Returning to Earth results in a relative space flight "anemia" as the plasma volume returns more quickly than the red blood cell volume (Alfrey et al., 1996). During one of the longer early Russian flights, there was an evaluation of the headward shifts of fluids using the "Chibis" device that "pulled" the fluids toward the feet (now called lower body negative pressure or LBNP). Tests were made using the LBNP device in conjunction with a high salt diet and forced fluids in an attempt to counter the lower hydration state of microgravity prior to returning to Earth's gravitational field (Charles et al., 1994). This reduced hydration status has been evoked to explain a portion of the orthostatic intolerance found upon return to Earth. It was hypothesized that the salt and water loading along with LBNP would improve the problem of orthostatic intolerance. Today crewmembers consume approximately one liter of saline immediately prior to deorbit burn and return to Earth. This replaces about half of the plasma volume decrement (Leach et al., 1996). Within a day or two after return to Earth, plasma volume returns to preflight levels. The percent of red blood cells (hematocrit) appears lower with increasing plasma volume. The red blood cell mass returns to preflight values over the next month or so. Nutritional requirements for fluids and iron are related to these physiological changes (Table 1).

Protein

One of the most consistent and physiologically important findings with space flight is the loss of body protein. Proteins are the "machinery" for all the metabolic functions in the body, from cell division to obtaining energy from foodstuffs to host-defense mechanisms. Loss of 30% to 40% of the total body protein invariably results in death from starvation (Cahill, 1970; Cahill, 1998; Keys et al., 1950). Intermediate losses are also a serious health hazard.

Microgravity perturbs the body's homeostasis by causing the loss of hydrostatic pressure, conflicting inputs into the neurovestibular system, and lack of physical tension on the musculoskeletal system. The effects on the musculoskeletal system are chronic, manifested by protein loss from muscles and calcium loss from bones with antigravity functions, most of which are located in the trunk and legs (Grigoriev and Egorov, 1992; LeBlanc et al., 1995; Thornton and Rummel, 1977; Whedon et al., 1977).

It is not yet known whether the protein loss reflects the adapted state or a chronic, continuing loss of body protein. Although all astronauts lose protein, there is some variability in the amounts lost. If the loss is part of the muscle's adaptive response to the new environment, which once attained is stable, then the problem is finite and the focus needs to be on maintaining functional capacity in flight and facilitating recovery postflight. It is likely that the process is

one of adaptation to a new steady state. But there is an important caveat. If there is an energy deficiency, as has occurred on two of the three missions for which energy balance data are available (Rambaut et al., 1977a, 1977b; Stein, unpublished), then protein synthesis is decreased. On Skylab, most of the protein loss occurred in the first month, but losses continued into the third month (Leach et al., 1983; Leonard et al., 1983; Whedon et al., 1977). In a finding from the Mir space, true adaptation probably did not occur (Stein, unpublished). In summary recommended protein intake should be near ground-based recommendations, however, without adequate energy intake, protein losses will continue despite protein intake.

Gastrointestinal Changes

There are gastrointestinal changes in space flight. For instance, gaseous stomach occurs due to the inability of gases to rise. The effect of chronic inactivity increases transit time and potentially changes gastrointestinal microflora (Lane et al., 1993). Furthermore, the effects of microgravity are presumed to alter the physical contact between gastric contents and the gastrointestinal mucosal cells. Anecdotal information suggests constipation is common in flight; however, this prevalence has not been documented. Many crewmembers consume mild laxatives during flight to remediate potential constipation. However, logically the cephalad-fluid shifts in combination with commonly observed dehydration could affect gastrointestinal motility possibly through reduced splanchris flow. Hepatic function in space has not been measured directly in humans. Preflight-postflight comparison of some indirect measures of liver function has shown a statistically significant change in serum γ-glutamyltranspeptidase activity; the clinical significance of this finding is unclear (Lane et al., 1993). Gastrointestinal changes may impact nutritional status, either through changes in appetite or absorption.

Taste

Anecdotal information suggests that thirst and appetite change during space flight. Three studies have specifically examined changes in sensitivity for odors and tastes during space flight. Heidelbaugh et al. (1975) measured taste thresholds and aroma identification ability preflight, inflight and postflight. Taste tests were performed with paper impregnated with onion, orange, bitter, sour, sweet and salt. Aromas were tested with microencapsulated aromas impregnated on scratch and sniff paper. The aroma tests indicated no evidence of any change in ability to identify aromas tested. The taste tests were highly individualized and indicated that shifts in thresholds occurred for some crewmembers. Weightlessness did not appear to affect thresholds. Watt et al. (1985) measured the detection and recognition threshold sensitivities of two astronauts to sweet, salty, sour and bitter tastes and to lemon, mint and vanilla odors. In comparing flight data with preflight measurements, they found no impairment of astronauts' abilities to identify odors. Although they found some shifts in the threshold levels for detection of some taste/flavor sensation, these shifts were highly individualized and were not statistically different. Ground-based studies (Rice et al., 1996) which simulated the nasal congestion of space flight also found no consistent changes in odor and taste perception. This study used an analog of space flight, -6° head-down supine bed rest. Six subjects were place in this position for 15 days. Their taste and odor sensitivities were determined prior to bed rest, during bed rest when there was nasal congestion, and after cessation of bed rest. Taste was measured using sucrose, sodium chloride, citric acid, quinine, monosodium glutamate, and capsaicin while odor

was measured using the volatile compounds isoamylbutyrate and menthone. Neither bed rest per se nor nasal congestion affected these measures of taste and odor sensitivities. However, the anecdotal reports from crewmembers suggest that there are changes in taste and odor sensitivity for some crewmembers, both of which changes would affect appetite, especially for certain foods.

Summary
Understanding nutrition metabolism during space flight is essential for the development of strategies to prevent changes in lean body mass and especially muscle performance. This involves consumption of energy and protein least the levels required on Earth. Maintenance of optimal performance includes consumption of all the nutrients summarized in Table 1 as well as a high quality food system.

Table 1
Daily Nutritional Requirements for International Space Station Missions Up To 360 Days

Nutrient	Units	Requirement
Energy	kilojoules (kilocalories)	WHO[A] equation
Protein	% total energy consumed	12--15
Carbohydrate	% total energy consumed	50
Fat	% total energy consumed	30-35
Fluid	ml per MJ consumed or ml per/kcal	238-357 or 1.0-1.5 or 2000 ml/d
Vitamin A	(µg retinal equivalent)	1000
Vitamin D	(µg)	10
Vitamin E	(mg a-tocopherol equivalent)	20
Vitamin K	(µg)	80
Vitamin C	(mg)	100
Vitamin B12	(µg)	2
Vitamin B6	(mg)	2
Thiamin	(mg)	1.5
Riboflavin	(mg)	2
Folate	(µg)	400
Niacin	(NE or mg)	20
Biotin	(µg)	100
Pantothenic Acid	(mg)	5
Calcium	(mg)	1000-1200
Phosphorus	(mg)	1000-1200 <1.5 times Ca intake
Magnesium	(mg)	350
Sodium	(mg)	1500-3500
Potassium	(mg)	3500
Iron	(mg)	10
Copper	(mg)	1.5-3.0
Manganese	(mg)	2.0-5.0
Fluoride	(mg)	4
Zinc	(mg)	15
Selenium	(µg)	70
Iodine	(µg)	150
Chromium	(µg)	100-200

[A]Individual energy requirements are calculated using the WHO equation accounting for

Table2. In-flight Intake of Apollo, Skylab, and Shuttle Astronauts

	Apollo (n=33)	Skylab (n=9)	Shuttle(n=26)
Energy Intake (MJ/d) (1 MJ=238 kcal)	7.9 ± 1.7[A]	11.9 ± 1.3	8.9 ± 2.0
% WHO-predicted energy requirements	64.2 ± 13.6%	99.1 ± 8.2%	74.0 ± 16.2%
Protein intake (g/d)	76.1 ± 18.7	111.0 ± 18.4	79 ± 19
Protein intake (% of kJ intake)	16.3% ± 2.1%	15.5% ± 1.2%	15% ± 3%
Carbohydrate intake (g/d)	268.8 ± 49.1	413.3 ± 59.3	309 ± 73
Carbohydrate intake(% of kJ intake)	58.1% ± 7.1%	58.1% ± 4.4%	59% ± 5%
Fat intake (g/d)	61.4 ± 21.4	83.2 ± 13.8	63 ± 18
Fat intake (% of kJ intake)	28.8% ± 5.4%	26.4% ± 3.8%	27% ± 4%
Water (ml/d)	1647 ± 188[B]	2829 ± 529	2285 ± 715
Sodium (mg/d)	2039.2 ± 672.7	5283.4± 1012.4	4047± 902
Potassium (mg/d)	2183.4 ± 896.4	3909.7 ± 612.2	2407 ± 548
Calcium (mg/d)	774 ± 212	902 ± 152	848 ± 213
Phosphorus (mg/d)	1121±324.6	1784.6 ± 297.1	1240 ± 306
Magnesium (mg/d)		315.78 ± 63.7	296 ± 75
Iron (mg/d)			15 ± 4
Zinc (mg/d)			12 ± 3

[A] Data are expressed as mean ± SD

[B] Water intake data are the mean ± SD for 3 crewmembers

^Data before flight are not available for the Apollo crewmembers
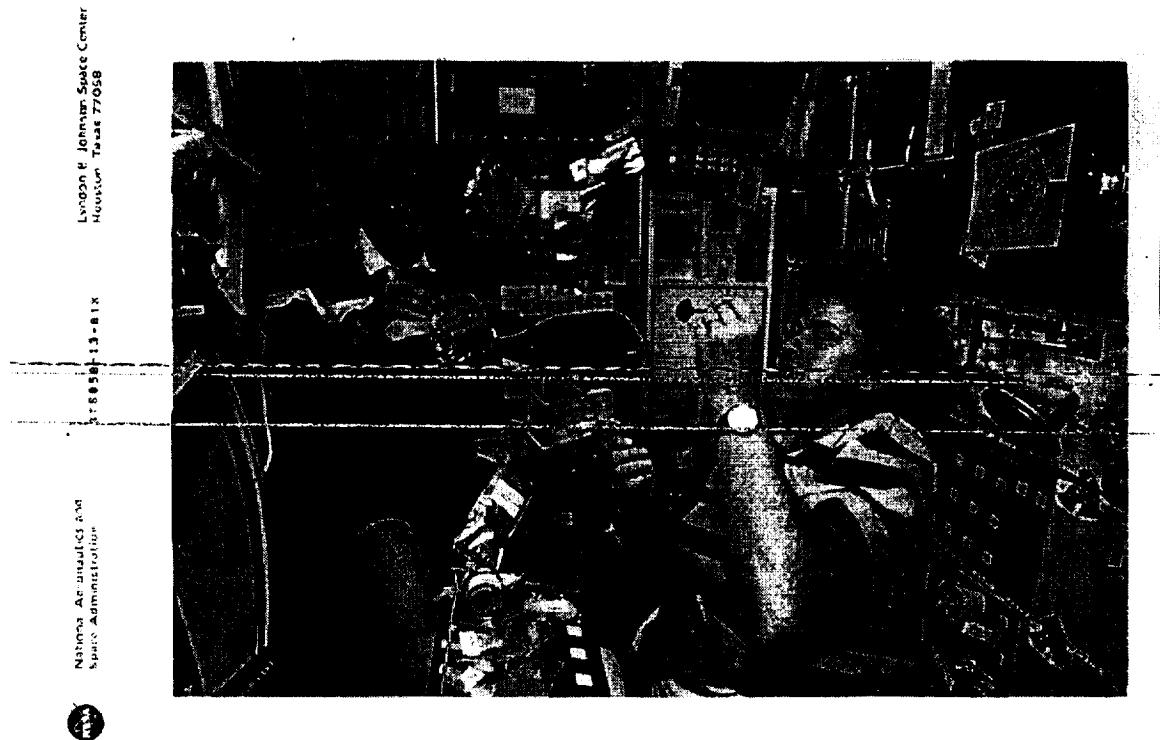
Figure 1. Astronauts John Blaha and Shannon Lucid share a meal aboard STS-58 in 1993
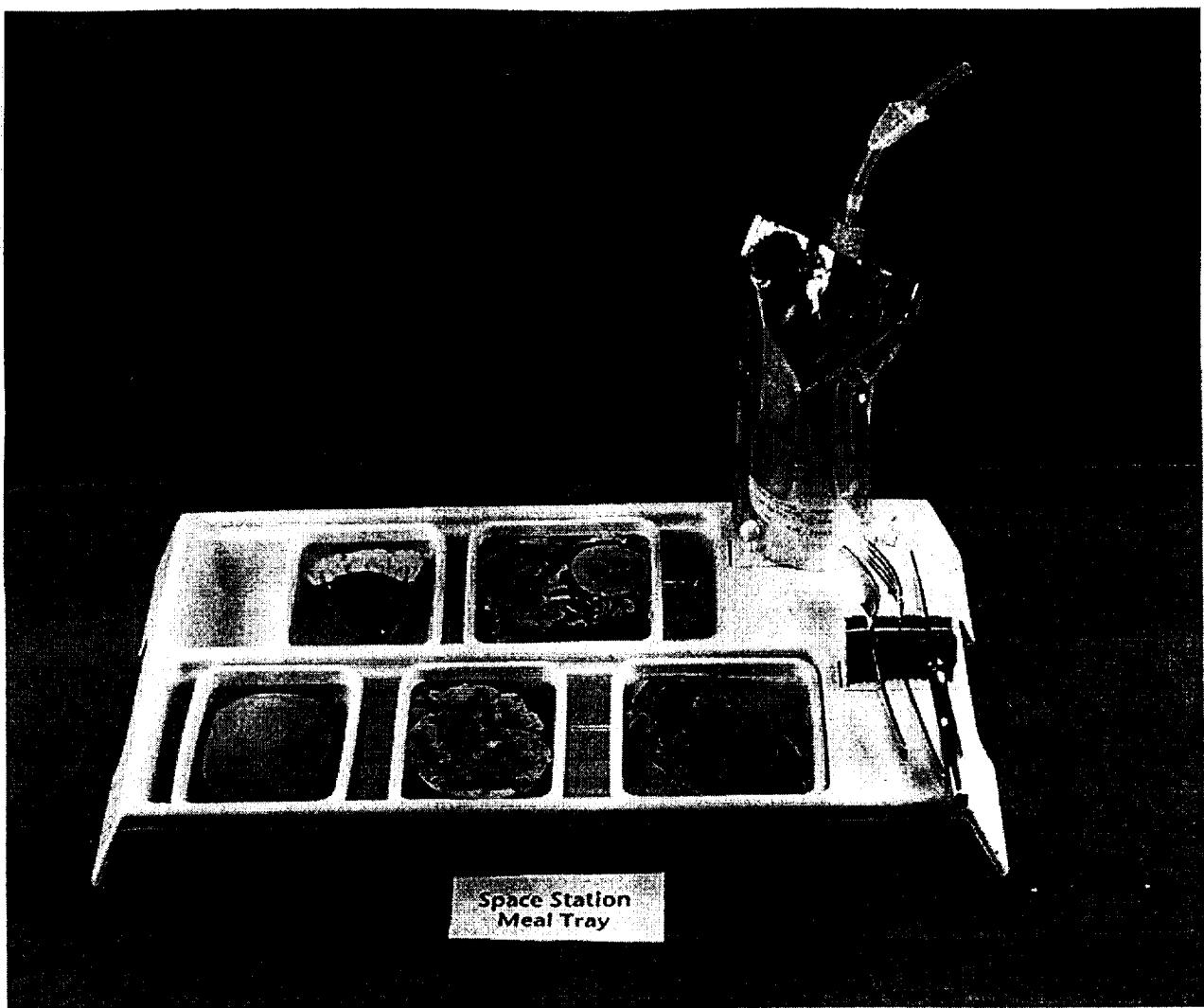
Figure 2

Table3. Estimates of Total Energy Expenditure During Space Flight (Mean±SD)

Mission	Method	n	Typical duration (days)	Body mass, preflight (Kg)	TEE, preflight (MJ/d)	TEE, in flight (MJ/d)	PAL, in flight	Ref
Vostok	CO_2 abs[1]		4	67	NA	8.0	1.2	Chirkov, 1973
Gemini	CO_2 abs	6	8			9.2		Lachance, 1967
Salyut	CO_2 abs	2	18	67	NA	9.6	1.4	Chirkov, 1973
Space Shuttle	CO_2 abs	27			NA	11.3±2.5		Lane, 1992
Skylab	I/B[2]	9	28	ca. 71	12.4±1.9	11.4±1.4[3]	1.6	Rambaut et al, 1977
Skylab	I/B	6	29-56[4]	ca. 71	12.8±1.6	12.0±0.3	1.7	Rambaut et al, 1977
Skylab	I/B	3	60-84[4]	ca. 71	12.0±1.3	12.5±0.6	1.75	Rambaut et al, 1977
Space Shuttle	DLW[5]	13	11	77	12.4±2.3	11.7±1.9	1.6	Lane et al, 1997

[1]CO_2 abs=Amount of CO_2 captured in absorption units.
[2]I/B=metabolizable energy intake plus change in body energy stores.
[3]=$p<0.05$ vs preflight.
[4]Indicates the time span for the metabolic period.
[5]DLW=doubly labeled water.

Insert Table – Implementation Timeline for Food System

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